Prediction of the Pressure Signature of a Ship in a Seastate

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LONG-TERM GOAL

Presently, all US ship mine vulnerability studies are based on the restrictive assumption that the ship is traveling through a calm sea. Our goal is to remove this restriction and thereby allow a more accurate assessment of ship vulnerability to sea mines.

OBJECTIVES

We are developing a model to predict the pressure field surrounding a ship advancing in a seaway. This pressure field consists of a steady component due to the forward motion of the ship and an unsteady component due to the oscillatory motions induced by the incoming waves. We are particularly interested in predicting the pressure signature on the seafloor, because this is where pressure-sensing mines are typically located. Since the ship pressure field decays with depth, high-frequency components of that field are filtered to a greater extent as depth increases. Additionally, the mine samples the ambient pressure field at varying but relatively low frequency. Both of these observations suggest the need for a model that includes a seafloor and is accurate at low frequencies. Most conventional strip theories assume the fluid to be infinitely deep and are valid only for high frequencies. They are not appropriate for our purpose, which is why we have chosen a three-dimensional formulation.

APPROACH

Our first step was to derive the finite-depth 3D Green function corresponding to a translating source with an oscillating strength. We confined our attention to simulations in the frequency domain. These solutions assume a sufficient time has passed since the ship first encountered the waves, and all motion transients have dissipated. The frequency-domain formulation is computationally efficient and therefore more suitable for vulnerability assessment models. Next, we developed an algorithm to numerically evaluate the Green function. The integrals in the Green function were evaluated using an adaptive quadrature. Before we could implement the Green function into a panel program, we needed to prove that the flow field can be represented by a source distribution over the submerged hull surface and along a contour where the hull intersects the free surface. This representation is equivalent to that in the infinite-depth case. Once the flow field can be represented by a source distribution, a panel program can be developed to compute the motions of a ship in waves and the resulting pressure field.

WORK COMPLETED

Derived the finite-depth 3D Green function for a translating and oscillating source.
Developed a numerical algorithm to compute the Green function and its derivatives.

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Showed that the flow field can be represented by a source distribution over the submerged hull surface and along a contour where the hull intersects the free surface. This representation is the same as in the case where the depth is infinite.

Developed a panel program that incorporates the Green function and computes the motions and pressure field of a ship advancing in waves. The program uses the above representation of the flow field.

RESULTS

The finite-depth 3D Green function at the field point (x,y,z) corresponds to a translating source with an oscillating strength of frequency σ located at (ξ,η,ζ) and is expressed as

$$
\begin{aligned}
G = {} & \frac{1}{r} + \frac{1}{r_2} - 2\int_0^{\infty} \frac{e^{-kh}\cosh(k(z+h))\cosh(k(z\ +h))J_0(kR)}{\cosh(kh)}dk \\
& - \frac{2}{p}\int_0^{\bar{q}}\int_0^{\infty} \frac{wF(k)e^{ik(x-x)\cos q}}{(kU\cos q + s)^2 - w^2}dkdq - \frac{2}{p}\int_q^{p/2} pv\int_0^{\infty} \frac{wF(k)e^{ik(x-x)\cos q}}{(kU\cos q + s)^2 - w^2}dkdq \\
& - \frac{2}{p}\int_0^{p/2} pv\int_0^{\infty} \frac{wF(k)e^{-ik(x-x)\cos q}}{(kU\cos q - s)^2 - w^2}dkdq - \int_q^{p/2} \frac{iF(k_1)e^{ik_1(x-x)\cos q}}{U\cos q - Cg(k_1)}dq \\
& + \int_q^{p/2} \frac{iF(k_2)e^{ik_2(x-x)\cos q}}{U\cos q - Cg(k_2)}dq + \int_0^{p/2} \frac{iF(k_3)e^{-ik_3(x-x)\cos q}}{U\cos q + Cg(k_3)}dq \\
& - \int_0^{p/2} \frac{iF(k_4)e^{-ik_4(x-x)\cos q}}{U\cos q - Cg(k_4)}dq
\end{aligned}
$$

where *pv* indicates the principal value of the integral and

h = fluid depth
$R^2 = (x-\xi)^2 + (y-\eta)^2$
$r^2 = R^2 + (z-\zeta)^2$
$r_2^2 = R^2 + (z+\zeta+2h)^2$
J_0 = Bessel function of the first kind of order zero
U = speed of the source

The wave frequency ω is related to the wave number k through the dispersion relation

$$w^2 = gk\tanh(kh)$$

where g is the gravitational constant. The group velocity $C_g(k)$ is also a function of k and is defined as

$$C_g(k) = \frac{\partial w}{\partial k}$$

The function $F(k)$ is

$$F(k) = \frac{w \cosh(k(z+h)) \cosh(k(z\ +h)) \cos(k(y-h)\sin q)}{\cosh(kh)\sinh(kh)}$$

For $\bar{q} \leq \theta \leq \pi/2$, the poles k_1 and k_2 are the two zeroes of the denominator of the fifth term of *G*, i.e., k_1 and k_2 are the roots of the equation

$$(kU \cos q + s)^2 - w^2 = 0$$

Here, we assume that $k_1 < k_2$. Similarly, k_3 and k_4 are the two zeroes of the denominator of the sixth term of *G*. They are the roots of the equation

$$(kU \cos q - s)^2 - w^2 = 0$$

The poles k_n, n=1,2,3,4 are functions of θ, and k_3 and k_4 exist for $\theta \in [0,\pi/2]$. Thus, the range of integration of the sixth term and the last two integrals is from 0 to π/2. The poles k_1 and k_2 exist only for $\theta \in [\bar{q}, \pi/2]$, where $\bar{q}$ is defined below. The fourth and fifth terms of *G* differ only in the range of θ integration. However, the fourth term contains no singularities and can be integrated numerically without any difficulties whereas the fifth term contains two singularities k_1 and k_2.

The definition of $\bar{q}$ is rather complex. Its value depends on U, h and σ. When h and σ are given, we can define two values $\bar{k}$ and $\bar{U}$ where $\bar{k}$ is the solution of the equation

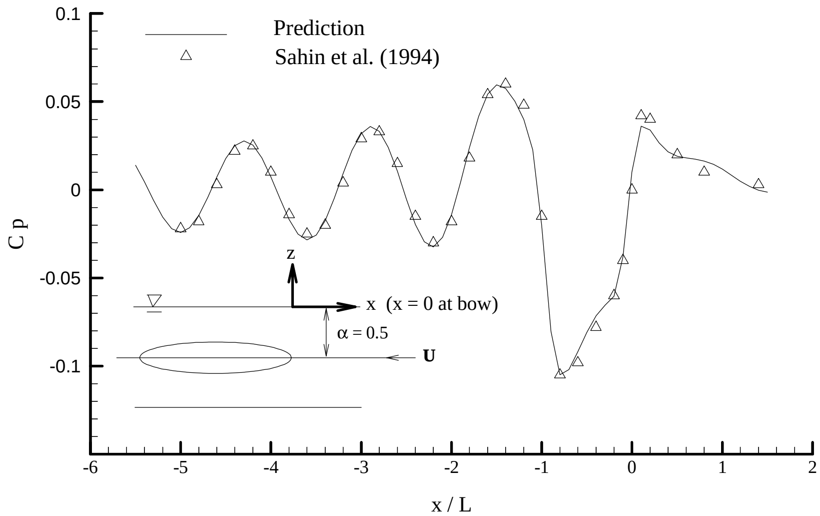
$$w(\bar{k}) - \bar{k} C_g(\bar{k}) = s$$

and $\bar{U}$ is given as

$$\bar{U} = C_g(\bar{k})$$

For $U < \bar{U}$, $\bar{q}$ =0, and the fourth term vanishes. All the remaining integrations with respect to θ are from 0 to π/2. For $U > \bar{U}$, $\bar{q} = \cos^{-1}(\bar{U}/U)$.

We validated the Green function and the numerical algorithm used in its evaluation by computing the steady flow around a fully submerged Rankine body. The Rankine body was chosen for its simplicity. It can be represented by a single source-sink pair and approximates an underwater vehicle fairly well. The Green function for the steady flow problem is a special case of our more general translating and oscillating Green function. It is obtained by setting the frequency in our Green function to zero. The figure compares our results with those of Sahin *et al*. (1994). The Rankine body in this example has a length to diameter ratio of 7 and a length to depth ratio of 2.25. The hull centerline is located at mid-depth (α= z/d=0.5), and the Froude number is 0.7. The figure shows the axial distribution of bottom pressures directly below the body (y=0). Excellent agreement is observed.



IMPACT/APPLICATIONS

The primary purpose of this research was to improve the Navy's ability to assess ship vulnerability to sea mines. However, our model can also be used to design improved pressure-sensing mines.

RELATED PROJECTS

Under a Coastal System Station Internal Research task, Dr. Thai Nguyen is investigating the effects of a compliant, muddy seafloor on the motion of ships in waves. A different Green function was derived and computed in this case where there exists a thin, denser fluid layer, representing the mud layer, below a lighter upper fluid layer. However, the same panel program is used in both projects with the exception of the subroutine computing the Green function.

REFERENCES

I. Sahin, M.C. Hyman and T.C. Nguyen. 1994: Three-dimensional flow around a submerged body in finite-depth water. Appl. Math. Modelling, 18, 611-619.